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Data assimilation (DA) systems are evolving to meet the demands of convection-permitting models in the field of weather forecasting. A special interest group meeting of the Royal Meteorological Society brought together UK researchers looking at different aspects of the data assimilation problem at high resolution, from theory to applications, and researchers creating our future high resolution observational networks. The meeting was chaired by Dr Sarah Dance of the University of Reading and Dr Cristina Charlton-Perez from the MetOffice@Reading.

The purpose of the meeting was to help define the current state of high resolution data assimilation in the UK. The workshop assembled three main types of scientist: observational network specialists, operational numerical weather prediction researchers and those developing the fundamental mathematical theory behind data assimilation and the underlying models. These three working areas are intrinsically linked; therefore, a holistic view must be taken when discussing the potential to make advances in high resolution data assimilation.

1 Background

In 2003, a workshop was convened to assess the feasibility of a mesoscale nowcasting system [Dabberdt et al., 2005]. At that meeting the scientific challenges facing high resolution precipitation forecasting were identified as improving the simulation of convective processes within numerical models, improving knowledge of convective downdrafts and gusts from individual storms and improving the understanding of the initialisation of convection [Wilson and Roberts, 2006]. On the lack of high resolution three-dimensional observations of state variables
above the boundary layer, they noted there was “currently no observational
capability to fill this gap” [Dabberdt et al., 2005].

Around the same time, review articles were released summarising the state
of high resolution DA [Dance, 2004; Sun, 2005; Park and Županski, 2003]. In
all references the main problem addressed is the forecasting of precipitation at
fine space and time discretisations.

2 Current state of data assimilation and forecasting at high resolutions

At the present time, pressing issues with DA methods related to both the high
spatial and time resolution in the forecasting system are no longer limited to
precipitation forecasting. Issues discussed at this meeting could be grouped into
the following themes:

- lateral boundary conditions for nested models,
- nonlinearity of the models,
- scale disparities,
- background, model and observational errors and
- computational demands of DA at scales relevant to precipitation forecast-
ing.

Ad hoc networks of devices such as smart phones and vehicles have exploded
in size and functionality. These networks are currently being considered for
their feasibility to provide information to assimilate into meteorological models
[Mahoney and O'Sullivan, 2013]. These networks have the potential to provide
surface measurements at the resolutions required by future high resolution data
assimilation systems, however they will still lack the three-dimensional structure
desired to fill the aforementioned observation gap.

Numerical weather prediction has benefited greatly from an increase in avail-
able computational power. This has allowed the models to grow rapidly in com-
plexity and resolution, producing much more realistic simulations. Likewise the
number, type and quality of observations have increased, thanks to the expan-
sion of radar networks and increases in the number and quality of satellite data
products. However, the data assimilation techniques to combine these two areas
of science in order to initialise a forecast are not yet capable of utilising all the
modern advances in modelling and observation. As an example, only around 5%
of scatterometer data are assimilated into both global and limited area models
at the MetOffice, whereas in the global model only 24% of AMDARS data is
assimilated which increases to 68% in the high resolution model [personal com-
munication, MetOffice]. The reasons for the number of observations utilised in
models of different resolution are complicated and vary greatly by observation
type. In some cases it is due to the resolution of the observations, their temporal and physical spacing or the quality control procedures used. Hence impact studies of potential new observations are proving necessary to quantify the benefits of additions to observing networks [Eyre and Weston, 2013; Simonin et al., 2013a].

In the summer of 2012 during the London Olympic Games, the MetOffice demonstrated its numerical weather prediction (NWP) based nowcasting system using 4D-Var [Golding et al., 2013; Simonin et al., 2013b]. Nowcasts are very short-range, high resolution forecasts used to give a prompt, quantitative forecast of hazardous weather and precipitation. This was an advance on previous nowcasting systems which used extrapolation and heuristic techniques, and is described in Sun et al. [2013].

3 Scientific presentations

Dr Ali Rudd of the University of Reading began the presentations by talking on the subject of model errors in high resolution, hence convection-permitting, numerical weather prediction models. A random parameter perturbed physics scheme has been used to represent the uncertainties due to model error in a convective-scale research ensemble prediction system (1.5km-EPS). As a test case, they used a DIAMET [DIAMET, 2013] flight campaign case, during which measurements were made of a frontal wave with structures not captured by the Met Office UKV (1.5km) operational model forecast or the 1.5km-EPS control forecast. The random parameters scheme had the effect of changing the spread of the ensemble, but did not improve the forecast skill in capturing the banding observed (by radar) in the rainfall [Baker et al., 2014]. It is vital to understand these changes in ensemble spread in order to tune an ensemble data assimilation system such as the ensemble transform Kalman filter that was used.

Prof Rob Scheichl of the University of Bath spoke on multilevel approaches from numerical analysis which show great potential in the next generation of data assimilation applications. These included geometric multigrid methods for the fast solution of a linear system [Buckeridge and Scheichl, 2010] where the matrix in question is the background error covariance matrix from variational data assimilation. Techniques from multilevel methods for the efficient solution of stochastic PDEs were presented [Teckentrup et al., 2013] because they promise to improve the efficiency of particle filters.

Prof Slobodan Djordjevic of the University of Exeter spoke on high resolution modelling of urban flooding events [Chen et al., 2012a,b]. With satellite imagery used to generate a topological network of the area in question, a multi-layered approach to calculation of flood extents was shown to be close to a much more computationally expensive high resolution model. Case studies shown included flooding events on the Isle of Wight and in Dhaka, Bangladesh. These computational techniques can be used to inform drainage system re-design, emergency flooding evacuation plans and the health impacts of pollution. The feasibility of creating a real-time flood warning system in which satellite and in-situ
observations would be assimilated into such models was discussed.

Dr Lee Hawkness-Smith from the MetOffice@Reading Data Assimilation
Group presented work on the assimilation of radar reflectivity in high resolution
numerical weather prediction [Hawkness-Smith and Ballard, 2013]. Reflectiv-
ties were assimilated using 4D-Var into the Met Office Nowcasting Demostra-
tion Project model, an NWP-based nowcasting research system.

Dr John Lees-Miller of the University of Bristol spoke on extracting infor-
mation from wireless networks for traffic modelling [Lees-Miller et al., 2013].
Making use of Bluetooth devices found in mobile phones and those increasingly
built into motor vehicles, observations of traffic densities and speeds were used to
build a hidden Markov model for traffic flow. These novel observations brought
with them a number of challenges, including privacy considerations, missed de-
tections and difficulties in discerning what is being measured; for example, is
the device which is detected actually in a car or on a bicycle? One application
of the model is measuring whether traffic policy changes have made an impact
on the dynamics of the road network. The use of such observations as described
by Dr Lees-Miller shows promise as a way in which to provide high resolution
surface observations for use in NWP models.

Dr Barbara Brooks from the University of Leeds was the final speaker of
the meeting and presented work on improving NWP forecasts by the use of
remotely controlled aircraft measurements [Jonassen et al., 2012]. Unmanned
aerial systems (UASs) are being developed to reduce costs and increase both
spatial and temporal resolution of the observation network in areas that are
currently under-observed. The main application of a particular UAS was to act
as a reusable radiosonde. A range of available UASs was described in order to
highlight the wide range of measurements that can be made using these modern,
reusable devices.

4 Discussion

A well-attended discussion session followed the presentations to consider the
future of high resolution data assimilation. Techniques to adaptively improve
the representation of background error covariances are already being employed
in high resolution DA systems [Piccolo and Cullen, 2012; Browne et al., 2014].
These methods go some way to addressing scale disparities in nested models,
particularly those disparities which can impact the simulation of boundary layer
dynamics. However, it was generally agreed that due to the nested nature of
high resolution meteorological data assimilation systems, a considerable amount
of the larger forecast errors on the high resolution grid come from large-scale
or synoptic uncertainties. During the discussion, a number of open research
questions emerged as the most pressing to be considered:

• Errors in the boundary conditions for the high resolution model exist due
to intrinsic errors in the synoptic scale model and to the process of taking
the coarse data down to a fine scale. Should the high resolution data
assimilation system be tailored to incorporate these uncertainties in the
boundary conditions?

• A recent study [Baxter et al., 2011] has shown that large scale meteorological features may not be sufficiently well represented in a limited area
domain, thus posing difficulties for DA in the smaller domain. What scales
should one analyse in high resolution DA (just the small scale or also the
large scales)?

• In a future where NWP uses correlated observation errors, how do the
scales implicit in the background and observation error correlations inter-
act?

The future of observational networks were discussed, specifically the net-
works which are not being designed or run specifically for meteorological ap-
lications. For example, important meteorological data is being extracted from
existing networks such as AMDAR [AMDAAR, 2013] and mode-S data [de Haan,
2011; de Haan and Stoffelen, 2012; Strajnar, 2012] from air traffic, humidity
measurements from global positioning systems [de Haan, 2013] and road traffic
data [Mahoney and O’Sullivan, 2013]. Increasingly, cheap sensors found in mo-
 bile phones are being adapted for use in all kinds of observational networks. If
such sensors prove to be the most important part of a meteorological observa-
tional network then the agencies which rely on them will come under increasing
pressure to control them in order to have confidence in their resilience.

• How will operational centres ensure the security of new ad-hoc networks
of observations?

Making full use of all of the available meteorological observations will still be
limited by the amount of computational power available to operational centres.
In the next generation of data assimilation systems more value may be gained
by incorporating information such as error structures in observations [Stewart
et al., 2008, 2013b; Weston, 2011; Stewart et al., 2013a; Bormann and Bauer,
2010] instead of simply increasing the number of observations.

• What gains could be made in forecasting by including observational error
structures in the data assimilation process compared with simply increas-
ing the number of observations?

In order to seek the greatest improvement of forecast skill in all applications
of atmospheric science, data assimilation must be heavily invested in. Only in
doing so will the gap between modern models of atmospheric dynamics and high
resolution observations be bridged in a rigorous way. Whilst the use of devel-
opment systems or test-beds were strongly encouraged a decade ago [Dabberdt
et al., 2005], the ability for researchers to test their advances using operational
systems and access any impact of new types of observations remains rather
limited. Systems like the Data Assimilation Research Testbed (DART) [Anders-
on et al., 2009], OpenDA [OpenDA, 2013] and the Parallel Data Assimilation
Framework (PDAF) [Nerger and Hiller, 2012] have the ability to test well developed DA methods on new models in various areas of science, but they do not easily lend themselves to testing novel DA methods with operational atmospheric science models. Adoption of functionality such as EMPIRE [Browne and Wilson, 2014] in operational forecast models would allow rapid testing and prototyping of academic concepts and theories in the most realistic settings.

The need for a flexible data assimilation system that can be accessed by researchers in academia and industry who are not in the operational centres remains an imperative goal that if created will benefit the whole atmospheric science community.

References


